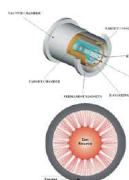
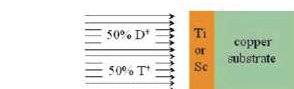


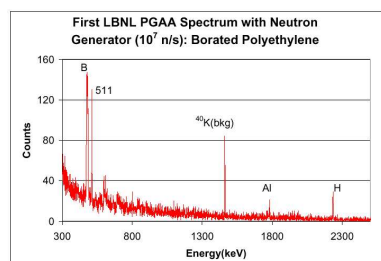
# PROMPT/DELAYED GAMMA-RAY NEUTRON ACTIVATION ANALYSIS (PGAA/NAA) SYSTEM FOR TOTAL, NONDESTRUCTIVE, IN SITU, ELEMENTAL ANALYSIS USING A NEUTRON GENERATOR

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Nuclear Science Division, Lawrence Berkeley National Laboratory

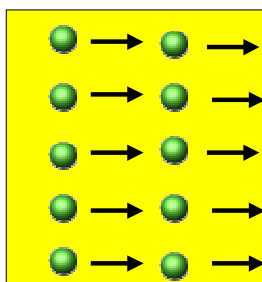
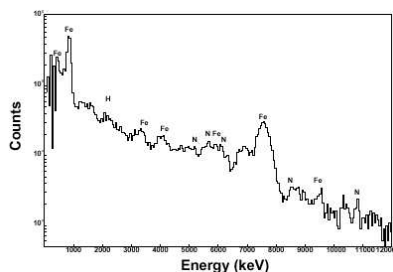
**LBNL Neutron Generator**

	D-D reaction	D-T reaction
Accelerator spec.	150 keV, 1.5 A	120 keV, 1 A
neutron yield [n/sec]	$10^{12}$	$10^{14}$
$\Phi_{\text{neut}} [\text{n/cm}^2/\text{sec}]$	$1.5 \cdot 10^7$	$5 \cdot 10^8$

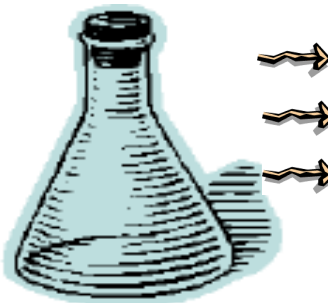


PGAA spectrum produced with prototype  
LBNL neutron generator.

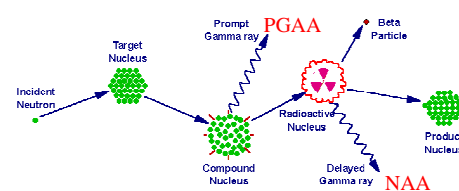
## SEARCHING FOR CONCEALED EXPLOSIVES



## MODERATED THERMAL NEUTRONS



## TARGET



PGAA uses thermal neutrons to induce prompt  $\gamma$  rays, unique for every element, for quantitative analysis. This technique is simultaneously sensitive to the entire periodic table. Detection limits typically range from ppb to 0.1% depending on cross section. The  $\gamma$  rays from decay of radioactive products produced by NAA can also be used for analysis. PGAA can be used to interrogate sealed containers because neutrons penetrate most materials.

### PGAA Elemental Sensitivity

PGAA Elemental Sensitivity																			Z Element	
atomic weight (capture) (scattering)		Detection Limit*																		
		<div><div>&lt; 10 ng</div><div>&lt; 1 mg</div><div>&lt; 100 mg</div><div>&lt; 1000 mg</div><div>No data</div></div>																		
3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne	11	Na	12	Mg	
6.94	6.94131	9.01	9.01218	10.81	10.81107	12.01	12.0107	14.01	14.0064	16.00	15.9991	18.99	18.9984	20.18	20.1797	22.99	22.9897	24.31	24.3047	
13	Al	14	Si	15	P	16	S	17	Cl	18	Ar	19	K	20	Ca	21	Sc	22	Ti	
26.98	26.98154	28.09	28.0859	30.97	30.9738	32.07	32.065	35.45	35.453	39.95	39.9624	39.10	39.0983	40.08	40.078	44.96	44.9559	47.88	47.883	
50.94	50.9415	52.00	51.9961	54.94	54.938	55.85	55.845	58.93	58.9332	58.69	58.6934	63.55	63.546	65.38	65.38	68.93	68.9256	72.64	72.64	
72.64	72.6405	74.92	74.9216	76.92	76.9209	78.97	78.9718	81.90	81.904	85.47	85.4678	89.90	89.9041	91.22	91.224	92.91	92.9064	95.94	95.94	
101.07	101.0653	102.97	102.9698	104.94	104.9359	106.92	106.9056	108.91	108.9048	110.91	110.9071	114.91	114.9046	118.91	118.9061	121.76	121.7583	124.91	124.9096	
138.91	138.9055	140.91	140.9079	142.91	142.9052	144.91	144.904	147.91	147.9017	150.91	150.9088	153.91	153.9094	156.91	156.9079	158.91	158.9054	161.91	161.9083	
162.57	162.5688	164.93	164.9303	167.76	167.761	169.92	169.926	172.91	172.9143	175.92	175.9224	178.92	178.9209	180.93	180.9327	183.85	183.849	186.93	186.934	
187.90	187.9018	190.93	190.9281	192.92	192.9222	194.99	194.9859	197.94	197.9407	199.92	199.9229	201.97	201.9728	203.97	203.9706	206.97	206.9688	208.98	208.9824	
208.9824	208.9796	210.98	210.9769	212.91	212.9042	214.90	214.8988	217.90	217.898	220.91	220.9096	223.91	223.9064	226.91	226.9036	228.91	228.9014	231.91	231.9042	
231.9068	231.9043	232.91	232.9092	235.04	235.0439	237.04	237.0438	238.03	238.0289	240.06	240.065	242.06	242.0627	244.06	244.0603	246.07	246.0674	248.07	248.065	
250.08	250.0764	252.08	252.0752	255.10	255.1027	257.10	257.0999	259.10	259.1017	261.10	261.1035	263.10	263.1053	265.10	265.1071	267.10	267.1089	269.10	269.1107	
270.10	270.1025	272.10	272.1043	274.10	274.1061	276.10	276.1079	278.10	278.1097	280.10	280.1115	282.10	282.1133	284.10	284.1151	286.10	286.1169	288.10	288.1187	
289.10	289.1205	291.10	291.1223	293.10	293.1241	295.10	295.1259	297.10	297.1277	299.10	299.1295	301.10	301.1313	303.10	303.1331	305.10	305.1349	307.10	307.1367	
309.10	309.1385	311.10	311.1403	313.10	313.1421	315.10	315.1439	317.10	317.1457	319.10	319.1475	321.10	321.1493	323.10	323.1511	325.10	325.1529	327.10	327.1547	
329.10	329.1565	331.10	331.1583	333.10	333.1601	335.10	335.1619	337.10	337.1637	339.10	339.1655	341.10	341.1673	343.10	343.1691	345.10	345.1709	347.10	347.1727	
349.10	349.1745	351.10	351.1763	353.10	353.1781	355.10	355.1799	357.10	357.1817	359.10	359.1835	361.10	361.1853	363.10	363.1871	365.10	365.1889	367.10	367.1907	
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389.10	389.2105	391.10	391.2123	393.10	393.2141	395.10	395.2159	397.10	397.2177	399.10	399.2195	401.10	401.2213	403.10	403.2231	405.10	405.2249	407.10	407.2267	
409.10	409.2285	411.10	411.2303	413.10	413.2321	415.10	415.2339	417.10	417.2357	419.10	419.2375	421.10	421.2393	423.10	423.2411	425.10	425.2429	427.10	427.2447	
429.10	429.2465	431.10	431.2483	433.10	433.2501	435.10	435.2519	437.10	437.2537	439.10	439.2555	441.10	441.2573	443.10	443.2591	445.10	445.2609	447.10	447.2627	
449.10	449.2645	451.10	451.2663	453.10	453.2681	455.10	455.2699	457.10	457.2717	459.10	459.2735	461.10	461.2753	463.10	463.2771	465.10	465.2789	467.10	467.2807	
469.10	469.2825	471.10	471.2843	473.10	473.2861	475.10	475.2879	477.10	477.2897	479.10	479.2915	481.10	481.2933	483.10	483.2951	485.10	485.2969	487.10	487.2987	
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509.10	509.3175	511.10	511.3193	513.10	513.3211	515.10	515.3229	517.10	517.3247	519.10	519.3265	521.10	521.3283	523.10	523.3301	525.10	525.3319	527.10	527.3337	
529.10	529.3355	531.10	531.3373	533.10	533.3391	535.10	535.3409	537.10	537.3427	539.10	539.3445	541.10	541.3463	543.10	543.3481	545.10	545.3499	547.10	547.3517	
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609.10	609.4075	611.10	611.4093	613.10	613.4111	615.10	615.4129	617.10	617.4147	619.10	619.4165	621.10	621.4183	623.10	623.4201	625.10	625.4219	627.10	627.4237	
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649.10	649.4435	651.10	651.4453	653.10	653.4471	655.10	655.4489	657.10	657.4507	659.10	659.4525	661.10	661.4543	663.10	663.4561	665.10	665.4579	667.10	667.4597	
669.10	669.4615	671.10	671.4633	673.10	673.4651	675.10	675.4669	677.10	677.4687	679.10	679.4705	681.10	681.4723	683.10	683.4741	685.10	685.4759	687.10	687.4777	
689.10	689.4795	691.10	691.4813	693.10	693.4831	695.10	695.4849	697.10	697.4867	699.10	699.4885	701.10	701.4903	703.10	703.4921	705.10	705.4939	707.10	707.4957	
709.10	709.4975	711.10	711.4993	713.10	713.5011	715.10	715.5029	717.10	717.5047	719.10	719.5065	721.10	721.5083	723.10	723.5101	725.10	725.5119	727.10	727.5137	
729.10	729.5155	731.10	731.5173	733.10	733.5191	735.10	735.5209	737.10	737.5227	739.10	739.5245	741.10	741.5263	743.10	743.5281	745.10	745.5299	747.10	747.5317	
749.10	749.5335	751.10	751.5353	753.10	753.5371	755.10	755.5389	757.10	757.5407	759.10	759.5425	761.10	761.5443	763.10	763.5461	765.10	765.5479	767.10	767.5497	
769.10	769.5515	771.10	771.5533	773.10	773.5551	775.10	775.5569	777.10	777.5587	779.10	779.5605	781.10	781.5623	783.10	783.5641	785.10	785.5659	787.10	787.5677	
789.10	789.5695	791.10	791.5713	793.10	793.5731	795.10	795.5749	797.10	797.5767	799.10	799.5785	801.10	801.5803	803.10	803.5821	805.10	805.5839	807.10	807.5857	
809.10	809.5875	811.10	811.5893	813.10	813.5911	815.10	815.5929	817.10	817.5947	819.10	819.5965	821.10	821.5983	823.10	823.6001	825.10	825.6019	827.10	827.6037	
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849.10	849.6235	851.10	851.6253	853.10	853.6271	855.10	855.6289	857.10	857.6307	859.10	859.6325	861.10	861.6343	863.10	863.6361	865.10	865.6379	867.10	867.6397	
869.10	869.6415	871.10	871.6433	873.10	873.6451	875.10	875.6469	877.10	877.6487	879.10	879.6505	881.10	881.6523	883.10	883.6541	885.10	885.6559	887.10	887.6577	
889.10	889.6595	891.10	891.6613	893.10	893.6631	895.10	895.6649	897.10	897.6667	899.10	899.6685	901.10	901.6703	903.10	903.6721	905.10	905.6739	907.10	907.6757	
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949.10	949.7135	951.10	951.7153	953.10	953.7171	955.10	955.7189	957.10	957.7207	959.10	959.7225	961.10	961.7243	963.10	963.7261	965.10	965.7279	967.10	967.7297	
969.10	969.7315	971.10	971.7333	973.10	973.7351	975.10	975.7369	977.10	977.7387	979.10	979.7405	981.10	981.7423	983.10	983.7441	985.10	985.7459	987.10	987.7477	
989.10	989.7495	991.10	991.7513	993.10	993.7531	995.10	995.7549	997.10	997.7567	999.10	999.7585	1001.10	1001.7603	1003.10	1003.7621	1005.10	1005.7639	1007.10	1007.7657	
1009.10	1009.7675	1011.10	1011.7693	1013.10	1013.7711	1015.10	1015.7729	1017.10	1017.7747	1019.10	1019.7765	1021.10	1021.7783	1023.10	1023.7801	1025.10	1025.7819	1027.10	1027.7837	
1029.10	1029.7855	1031.10	1031.7873	1033.10	1033.7891	1035.10	1035.7909													

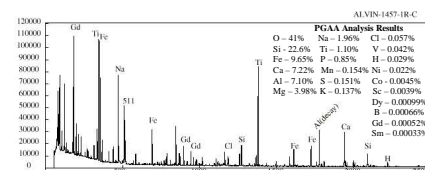
\* Per cm<sup>2</sup> based on 0.01 captures per second assuming 10<sup>6</sup> neutrons/cm<sup>2</sup> and neglecting gamma-ray detection efficiency

## PGAA ANALYSIS OF A CARGO CONTAINER

In this example, the LBNL neutron generator is operated in D+D mode to detect 500 lbs of  $\text{NH}_4\text{NO}_3$  hidden in a cargo container. The  $\gamma$ -ray spectrum is calculated with the computer code MCNP assuming  $2 \times 10^9$  incident neutrons are emitted next to a 40 ft cargo container. A single 6"x9" BGO detector is placed on the opposite side of the container. The 2.5 MeV neutrons from the source thermalize in the  $\text{NH}_4\text{NO}_3$ . This spectrum would be obtained in  $<0.1$  s with a  $10^{12}$  n/s LBNL neutron generator. The spectrum is dominated by the steel container walls, but gammas from nitrogen and hydrogen clearly visible.

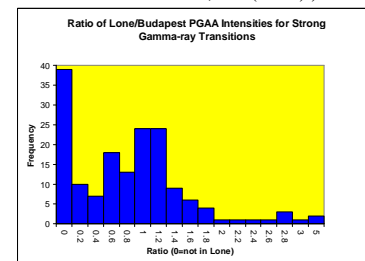


## DETECTORS



PGAA analysis of a deep-sea vent sample collected with the ALVIN submersible. Analysis was performed at the Budapest Reactor facility with a  $10^6$  n/s beam. Additional  $\gamma$  rays up to 9 MeV were observed. D.L.Perry, R.B. Firestone, *et al*, J. Anal. At. Spectrom. **16**, 1 (2001).

**DATABASE:** A new database of 33,000  $\gamma$  rays for PGAA analysis is being prepared by LBNL in collaboration with the IAEA and the Institute for Isotope and Surface Chemistry, Budapest. This database replaces the outdated Lone *et al* data (At. Data Nucl. Data Tables **26**, 511(1981).)



Ratio of the strongest  $\gamma$ -ray intensities from our new compilation to those of Lone *et al.* About 25% of these  $\gamma$  rays were not observed by Lone.

### Comparison of certified (NIST) and PGAA measured concentrations in river sediment

	CERTIFIED	PGAA
Element	Concentration%	Concentration%
Cr	2.96±0.28	≅2.96
Fe	11.3±1.2	11.5±0.3
K	1.2	1.4±0.1
Ca	2.9	3.0±0.1
Cd	0.00102±0.00009	0.00104±0.00003
Mn	0.078±0.010	0.077±0.011

## OTHER PGAA ANTITERRORISM APPLICATIONS:

- Forensic analysis of crime scenes
- Interrogation of nuclear materials
- Luggage screening
- Stand-off detection of explosives
- Landmine detection